CONVERSION OF MICROWAVE SIGNALS BY SUPERCONDUCTING FILMS IN THE RESISTIVE STATE

I.I. Yeru, S.A. Peskovatskiy and V.S. Sulima

(NASA-TM-77595) CONVERSION OF MICROWAVE SIGNALS BY SUPERCONDUCTING FILMS IN THE RESISTIVE STATE (National Aeronautics and Space Administration) 28 p HC A03/MF A01 N85-10843
CSCL 20L G3/76 Unclas 24167

Translation of "Preobrazovaniye Signalov SVCh Sverkhprovodnikovymi Plenkami v Rezistivnom Sostoyanii," Academy of Sciences Ukrainian SSR, Institute of Radiophysics and Electronics, Kharkov, Preprint 156, 1980, pp. 1-35.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 AUGUST 1984

ORIGINAL PAGE IS
OF POOR QUALITY

STANDARD TITLE PAGE

1. Report No. NASA TM-77595	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CONVERSION OF MICROWAVE SIGNALS BY SUPERCONDUCTING FILMS IN THE RESISTIVE STATE		5. Report Date August 1984
		6. Performing Organization Code
7. Author(s) I.I. Yeru, S.A. Peskovatskiy and V.S. Sulima		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11. Contract or Grant No. NASw-3541
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Preobrazovaniye Signalov SVCh Sverkhprovodnikovymi Plenkami v Rezistivnom Sostoyanii," Academy of Sciences Ukrainian SSR, Institute of Radiophysics and Electronics, Kharkov, Preprint 156, 1980, pp. 1-35.

16. Abstract

The main characteristics of a superconducting thin film microwave mixer, i.e., conversion efficiency and bandwidth are analyzed. The optimum operating regime of the nonlinear element is determined. Results of calculations are compared with the experimental ones. Experimental data on the noise in the superconducting films in a wide frequency range are presented.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unlimited-Unclassified

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22.
Unclassified	Unclassified	28	

CONVERSION OF MICROWAVE SIGNALS BY SUPERCONDUCTING FILMS IN THE RESISTIVE STATE

I.I. Yeru, S.A. Peskovatskiy and V.S. Sulima

Introduction

Thorough cooling of a microwave range receiver to cryogenic temperatures ($T<80$ K) permits an appreciable reduction of its natural noise level. At the same time, work at such low temperatures makes it possible to use elements in this equipment the action of which is based on the use of a number of special physical effects and phenomena peculiar only to this temperature interval. One such possibility is the use of the nonlinear properties of superconductors for the conversion of microwave signals. /3*

Basically those phenomena in superconductors which could be used in radio engineering equipment had been studied by the beginning of the 1970s. Works appeared which reported the development of individual specimens of highly sensitive superconductor instruments, which stimulated further research in this area. Superconducting point contacts were used in these instruments however. They have a number of significant deficiencies: nonreproducibility of parameters; insufficient reliability and resistance to mechanical, thermal (especially to repeated cooling from room temperature to working temperature) and other effects.

Superconducting film elements are free of these deficiencies. /4
However, their properties were inadequately studied at the same time. Studies of the current-voltage characteristics (CVC) of superconducting films [1-6] indicated the possibility of conversion of microwave signals in these elements. Such a superconducting film mixer was previously discussed in [7]. Detailed study of the char-

*Numbers in the margin indicate pagination in the foreign text.

acteristics of superconducting nonlinear elements in microwave circuits, efficiency of conversion of microwave signals by means of them and their noise characteristics, as well as determination of the optimum operating regimes are necessary for resolution of the question of the use of such instruments.

The results of studies of these characteristics of nonlinear superconducting thin film elements and microwave mixers based on them are presented below.

I. Current-Voltage Curves of Superconducting Films

A characteristic feature of the current-voltage curves of thin ($d<\lambda_L$, ξ_0, where λ_L is the London penetration depth and ξ_0 is the coherence length) superconducting films with a constant cross section preserved over some length (ℓ) is the presence of a "vertical" section in them (Fig. 1) [1-4]. The steepness of the curve in this section is very high ($r_d=\frac{du}{di}>>\frac{u}{i}$), and it is determined only by a geometric factor, the degree of constancy of the film cross section along its length. With increase in voltage, the "vertical" section changes to a normal resistance section but, with a decrease, the curve ends with a break at a voltage on the film below some U_{min} [1].

This shape of the current-voltage curves of long superconducting /5
films is due to the following circumstance. Upon destruction of superconductivity of the film by the current in it, a resistive (R) region of finite dimensions is formed in it, which is bounded by transition (RS) regions which are on the order of the diffusion length long. The steady length (resistance) of this R region, which develops in the film in the subcritical regime, proves to be proportional to the voltage on it with constant current density in the film. This leads to the formation of a "vertical" section in the current-voltage curve of the film. The speed of establishment of a steady length of this region with change in voltage is determined by the speed of movement of its boundaries. The latter as was es- /6

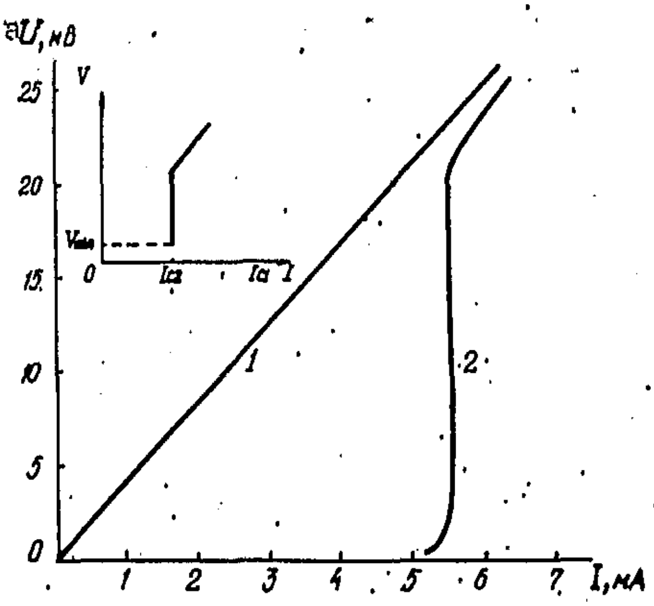

Fig. 1.

Key: a. U, mV

tablished in [8], is proportional to the deviation of the current density in the film from steady value J_{c2}, and it reaches 10^6 cm/s in tin films as $J \to J_{c1}$.

Elements with a continuous current-voltage curve in which this discontinuity is removed (Fig. 2) are more convenient for practical applications. It is sufficient for this to remove the superconductivity of one end of the film by some method [2].

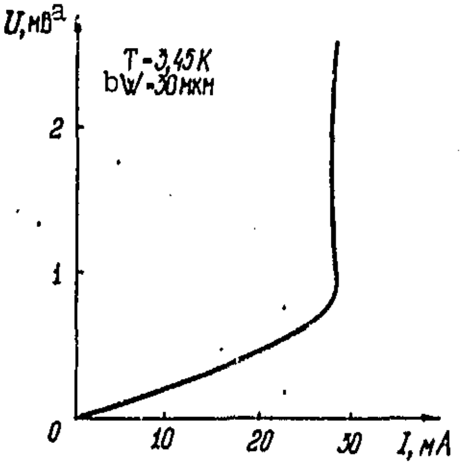

Fig. 2.

Key: a. U, mv
b. W=30 μm

The alternating current voltage applied to the resistive region of a superconducting film is displayed differently (depending on its rate of change) in the shape of its current-voltage curve recorded by direct current [5, 6]. Until the dimensions of the resistive region succeed in tracking the voltage change, its dynamic resistance in the "vertical" section of the current-voltage curve (r_d) remains the same as by direct current. The alternating current component in the film /7
is negligibly small under these conditions, and the shape of the current-voltage curve remains practically unchanged. At quite high frequencies (over 10^9 Hz for tin by our measurements), the dimensions of the resistive region practically do not track the alternating voltage, and the film behaves like a conventional resistor $r = \frac{u}{I}$ at these frequencies. This results in the appearance of alternating current

component $I_\sim$ in the film which in turn changes the steady voltage of the direct current flowing through the film. Analysis shows that the dependence of the direct current in the film on the microwave current can be presented in this case by the empirical expression

$$I(I_\sim)=\sqrt{I^2(0)-aI_\sim^2}\approx I(0)-\alpha(\omega)\frac{I_\sim^2}{I(0)}, \qquad (1)$$

where

$$\alpha\equiv\frac{a}{2}.$$

For tin, $\alpha(\omega)\ll 1$ at frequencies up to 10^8 Hz, and $\alpha(\omega)\gtrsim 0.5$ at a frequency of 10^{10} Hz.

The quadratic nature of relationship (1) indicates the possibility of detection and mixing of microwave signals by means of such superconducting films changed to the resistive state by the current. It is only necessary that the condition

$$\omega\gg\Omega_m\gg\Omega$$

be fulfilled, where ω is the carrier frequency, Ω_m is the characteristic reaction rate of the resistive region of the superconducting film to external electromagnetic perturbation, and Ω is the modulation frequency.

The shape of the current-voltage curve of the superconducting film in direct current and acted on by the microwave field will essentially depend on the conditions of matching the film with the microwave radiation source. The amplitude of the microwave current flowing through the resistive region of the superconducting film generally is /8

$$I_\sim=\frac{\sqrt{8Pr_i}}{r_i+r_\sim},$$

where P is the power of the microwave source, r_i is its internal resistance, $r_\sim$ is the resistance of the resistive region to microwaves. If it is taken into account that $r_\sim=r$ in microwaves ($\omega\gg\Omega_m$),

$$\frac{dI_\sim}{dU}=-\frac{\sqrt{8Pr_i}}{(r+r_i)^2}\frac{dr}{dU}=-\frac{1}{I_0}\frac{\sqrt{8Pr_i}}{(r+r_i)^2}\left(1-\frac{r}{r_d}\right),$$

where $\qquad I_0\equiv I \qquad$ with $\qquad I_\sim=0.$

By definition

$$\frac{1}{r_d} \equiv \frac{dI}{dU} = \frac{\partial I}{\partial U}\Big|_{I_\sim = const} + \frac{\partial I}{\partial I_\sim}\frac{dI_\sim}{dU}.$$

If $I_\sim$=const along the entire "vertical" section of the current-voltage curve, this section will be displaced parallel to itself with change in microwave power level and

$$\frac{\partial I}{\partial U}\Big|_{I_\sim = 0} \equiv \frac{1}{r_{do}}.$$

Besides, according to Eq. (1),

$$\frac{\partial I}{\partial I_\sim} = -\frac{2\alpha I_\sim}{I_o}.$$

Consequently, generally

$$\frac{1}{r_d} = \frac{1}{r_{do}} + \frac{2\alpha P}{U_o I_o}\frac{1}{r}\frac{8\sigma_r}{(1+\sigma_r)^3}\left(1 - \frac{r}{r_{do}}\right), \qquad (2)$$

where /9

$$U_o \equiv r I_o, \qquad \sigma_r \equiv \frac{r_i}{r}.$$

According to Eq. (2), the slope of the "vertical" section of the current-voltage curve practically does not depend on either the power of the microwave radiation source or on the bias voltage with $\sigma_r \gg 1$ (Fig. 3). Under close to matching conditions ($\sigma_r \approx 1$), the slope of the "vertical" section does not remain constant, but depends essentially on these parameters (Fig. 4).

II. Superconducting Film Microwave Videodetector

By using expression (1), it is easy to determine the current-power sensitivity (β) of a superconducting film as a microwave radiation videodetector: /10

$$\beta \equiv \frac{I(0) - I(I_\sim)}{P} = \frac{2\alpha}{U_o}.$$

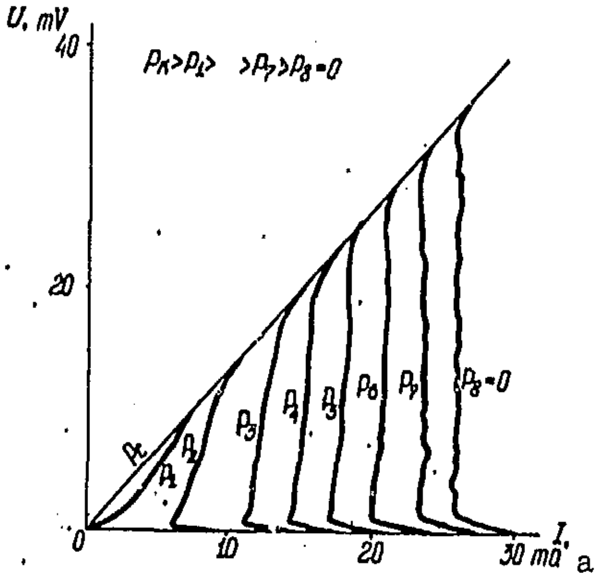

Fig. 3.

Key: a. I, mA

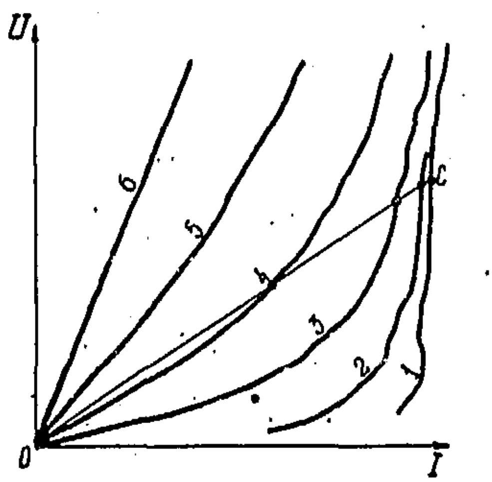

Fig. 4.

In tin films at T=2 K, U_{min} is not over 150-200 μV. Voltage of the same order of magnitude precedes the appearance of the "vertical" section on the current-voltage curves of these films from the nonsuperconducting end. Consequently, $U_0 \geqslant 150$-200 μV in tin films, and β in them can reach (3-5)·10^3 A/W in them. These estimates are confirmed by our direct measurements (10^3 A/W was obtained in tin). /11

As to the voltage-power sensitivity of such a videodetector, its value (βr_d) is theoretically limited in no way, since the slope of the "vertical" section of the current-voltage curve of the films in question is determined only by their configuration, and it can therefore be made as high as desired.

The detector described operates efficiently only at sufficiently high carrier frequencies when $\omega >> \Omega_m$ and therefore $r_\sim = r$. At the same time, the low frequency output resistance of this detector (r_d with $\Omega << \Omega_m$) greatly ex-exceeds the value of r. This indicates that the conversion efficiency of such a microwave detector

$$\eta = \frac{I^2_{hf} r_d}{I^2_{uhf} r}$$

can theoretically be made greater than one, if even $I_{\ell f} < I_{uhf}$. It should only be kept in mind that the output frequency band of the detector in question is compressed correspondingly in this detection regime (see below).

III. Superconducting Film Mixer

In the presence of a microwave current, the "vertical" section of /12 the current-voltage curve of superconducting films of the configuration under consideration can be described by the following (empirical) expression:

$$i = I_0 - \alpha \frac{I_\sim^2}{I_0}\left(1 - \frac{r}{r_d}\right) + \frac{U - U_0}{r_d}. \qquad (4)$$

Here, I_0 and U_0 are the steady current in the film and the voltage in it in the absence of a microwave current, and r_d is calculated in accordance with Eq. (2). According to Eq. (4), a change in microwave power level ($f \gtrsim 10^{10}$ Hz) incident on the superconducting film results in the appearance in the circuit containing this film of an alternating current component of frequency Ω at some frequency Ω ($< 10^9$ Hz). If active load r_Ω is connected in series (with alternating current of frequency Ω) to the film,

$$U - U_0 = r_\Omega (I_0 - i),$$

and consequently

$$i = I_0 - \frac{\alpha I_\sim^2 \left(1 - \frac{r}{r_d}\right)}{I_0 \left(1 + \frac{r_\Omega}{r_d}\right)}. \qquad (5)$$

As a consequence of the quadratic nature of relationship (5), upon the action on this film of two microwave signals

$$i_1 = I_c \cos \omega_c t,$$

$$i_2 = I_r \cos \omega_r t,$$

such that

$$I_c \ll I_r \text{ and } \Omega \equiv |\omega_r - \omega_c| \ll \omega_r. \qquad (6)$$

An alternating current component of difference frequency Ω ap- /13 pears in the load. With Eq. (6) taken into account, its amplitude will be

$$I_\Omega = \frac{2\alpha I_r I_c}{I_0} \, \frac{1 - \frac{r}{r_d}}{1 + \frac{r_\Omega}{r_d}}$$

We define the conversion efficiency (η) of such a converter:

$$\eta \equiv \frac{P(\Omega)}{P(\omega_s)} = \frac{I_\Omega^2 r_\Omega}{I_c^2 r_{\omega c}}.$$

Since $r_{\omega s}=r$ in microwave,

$$\eta = \alpha \frac{\beta P_r}{I_0} \frac{4\delta_r}{(1+\delta_r)^2} \frac{4\delta_\Omega}{(1+\delta_\Omega)^2} \frac{(1-k_1)^2}{k_1}, \qquad (7)$$

where P_r is the heterodyne power (at frequency ω_r) and

$$\delta_\Omega \equiv \frac{r_\Omega}{r_d}, \qquad k_1 \equiv \frac{r}{r_d}.$$

The nonlinear nature of the resistive section of the current-voltage curve of the superconducting film used in the mixer in question is dependent on the change in length of the resistive region in this film, which occurs with the change in voltage on it. The ultimate rate of movement of the resistive region boundaries will therefore limit (above) the range of intermediate (but not mixed) frequencies of such a mixer.

To estimate these limits, we will assume that the time change of resistance (length) of the resistive region is described by the expression

$$\dot{r} = v R_0, \qquad (8)$$

where R_0 is the resistance of a unit length of the resistive region and v is the rate of movement of its boundary.

In the general case,

$$\dot{u} = \dot{r} I + r \dot{I}. \qquad (9)$$

It is easy to show (Fig. 5) that /14

$$\frac{u-U_0}{r_d} + \frac{u-U_0}{r_d} + (I_0 - I)\frac{r}{r} = I_0 - I,$$

i.e.,

$$\frac{u-U_0}{r_e} = (I_0 - I)(1-k_1),$$

where

$$r_e = \frac{r_\Omega r_d}{r_\Omega + r_d}.$$

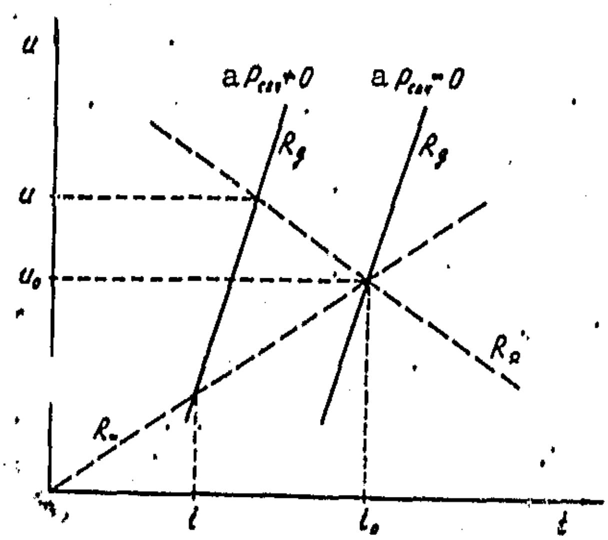

Fig. 5.

Key: a. P_{uhf}

Consequently,

$$i = -\frac{\dot{u}}{\tau_e(1-k_1)}. \qquad (10)$$

By substituting the results of Eq. (8) and (10) in Eq. (9), we obtain /15

$$\dot{u} = \frac{v k_q i}{1 + \frac{\tau}{\tau_e(1-k_1)}}. \qquad (11)$$

According to [7, 8]

$$v = v_0 \frac{I - I_{c2}}{I_{c1} - I_{c2}}.$$

In the resistive section of the current-voltage curve, $i = I_{c2}$ [2]. Therefore,

$$v = v_0 \frac{\Delta i}{i} \frac{1}{\gamma - 1}, \qquad (12)$$

where

$$\gamma \equiv \frac{I_{c1}}{I_{c2}}.$$

Thus,

$$\dot{u} = \frac{v_0}{l_r} \frac{\tau \tau_e}{\tau_e + \frac{\tau}{1-k_1}} \frac{1}{\gamma - 1} \Delta i, \qquad (13)$$

where ℓ_r is the length of the resistive region, the minimum value of which is limited by the diffusion lengths of quasiparticles in the film [2].

It is evident from Fig. 5 that

$$\Delta i = i - \frac{u}{r_\Omega}, \qquad (14)$$

where i and u are the instantaneous values of the current and voltage of frequency Ω.

By substituting Eq. (14) in Eq. (13), we obtain

$$\dot{u} + \Omega_m u = A, \qquad (15)$$

where

$$\Omega_m \equiv \frac{v_t}{l_t}\,\frac{1}{\gamma-1}\,\frac{k_1}{1+k_2\left[\frac{1+\sigma_\Omega}{1-k_1}\right]};$$
$$A \equiv i r_\Omega \Omega_m; \qquad (16)$$
$$k_2 \equiv \frac{r}{r_\Omega}; \qquad \sigma_\Omega \equiv \frac{r_\Omega}{r_d}.$$

In this manner, /16

$$u(\Omega) = u(0)\,\frac{1}{1+j\frac{\Omega}{\Omega_m}}, \qquad (17)$$

where $u(\Omega)$ is the amplitude of the voltage in the film at frequency Ω and $u(0)$ is the voltage amplitude in the film at "zero" frequency.

Since the power in the load r_Ω at frequency Ω equals

$$P(\Omega) = \frac{u(\Omega)\,u^*(\Omega)}{r_\Omega},$$

it becomes clear that Ω_m is the value of the intermediate frequency at which the conversion efficiency of the mixer in question drops to half that at low frequencies ($\Omega \ll \Omega_m$).

We discuss two basic possible operating regimes of a superconducting film mixer.

1. $\sigma_r \gg 1$. In this mixer operating regime, the change in length (resistance) of the resistive region of the film will have practically no effect on the heterodyne current ("fixed heterodyne current" regime).

According to Eq. (2), $r_d = r_{d0}$ in this regime and

$$\eta = \frac{\alpha}{2}\,\frac{4\sigma_c\sigma_r}{(1+\sigma_c)^2}\,\frac{4\sigma_\Omega}{(1+\sigma_\Omega)^2} \qquad (18)$$

and with $\sigma_\Omega \sim 1$, $\sigma_c \sim 1$,

$$\eta \approx \frac{\alpha\sigma_r}{2} \qquad (19)$$

and consequently, the mixer conversion efficiency in this regime can

become significantly greater than unity.

In conventional designs of a mixer with a common signal and heterodyne input however, a severe discrepancy at the input does not permit achievement of such conversion efficiencies. Separate heterodyne and signal source connection components to the superconducting film should therefore be used in this mixer operating regime. This /17 makes possible a good match of the mixer input to the signal frequency with the mismatched heterodyne retained in this case, and it thereby permits actual "downward" frequency conversion with amplification.

As to the intermediate frequency bands of such a mixer in the "fixed heterodyne current" regime, since $r_{\Omega} \approx r_{do} \gg r$,

$$\Omega_m \approx \frac{v_0}{l_n} \frac{1}{\gamma - 1} k_2', \tag{20}$$

i.e., conversion with amplification is accompanied by significant constriction of the output frequency band of the mixer.

2. $\sigma_r \approx 1$. In distinction from the preceding, in this mixer operating regime ("fixed heterodyne power" regime), heterodyne current I_r depends essentially on the length (resistance) of the resistive region.

An advantage of this regime over the "fixed current" regime is the possibility of the use of a conventional mixer design with a common signal and heterodyne connection element in this case.

According to Eq. (2), the maximum intermediate frequency band is reached when $r \approx r_{\Omega} \ll r_{do}$:

$$\Omega_m \simeq \frac{v_0}{l_n} \frac{1}{\gamma - 1} \frac{1 + \frac{\beta P_r}{I_0}}{1 - \frac{\beta P_r}{I_0}}. \tag{21}$$

It follows from the expression obtained that the intermediate frequency band can be made as large as desired as $\beta P_r \to I_0$. Since $k_1 \to 1$ in this case however, mixer conversion efficiency η will tend

toward zero according to Eq. (7). With the slight dependence of parameter Ω_m on the r/r_Ω ratio taken into account, it is therefore more advantageous to operate with $r<r_\Omega \approx r_d$ in this regime, when

$$\eta \approx \alpha \frac{(1-k_1)^2}{k_1}, \tag{22}$$

and the Ω_m frequency band is nevertheless quite wide /18

$$\Omega_m \approx \frac{v_s}{l_T} \frac{1}{\gamma-1} k_2.$$

All the results for the frequency characteristics of the superconducting film mixer are completely valid for the analogous characteristics of the superconducting videodetector discussed above.

The estimates we have made based on the equations obtained show that the superconducting film mixer discussed can have a conversion efficiency on the order of 0.5 in the cm range (in the absence of the amplification effect) and an intermediate frequency band of at least several hundred megahertz.

Experiments on superconducting tin films [9] carried out in the 3 cm range confirmed the correctness of all these conclusions.

The presence of the nonsuperconducting end in the superconducting film not only eliminates the discontinuity of its current-voltage curve, it permits a current-voltage curve with a negative slope of the "vertical" section ($r_d<0$) to be obtained with the appropriate configuration. (It is sufficient for this that the width of the film decrease with distance from its nonsuperconducting end.)

In this case, the basic relations of the mixer are rewritten as

$$\frac{1}{\tau_d} = \frac{1}{\tau_{do}} - \frac{\beta P_r}{I_0} \frac{8\delta_r}{(1+\delta_r)^2}, \tag{23}$$

$$\eta = \alpha \frac{\beta P_r}{I_0} \frac{4\delta_r}{(1+\delta_r)^2} \frac{4\delta_c}{(1+\delta_c)^2} \frac{4\delta_n}{(1-\delta_n)^2} \frac{(1+k_1)^2}{k_1}, \tag{24}$$

$$\Omega_m = \frac{v_s}{l_T} \frac{1}{\gamma-1} \frac{k_2}{\left[1+k_2 \frac{1-\delta_n}{1+k_1}\right]}. \tag{25}$$

It is easy to determine that, in the "fixed heterodyne power" regime with $r_d<0$, the expressions for η and Ω_m with $|\sigma_\Omega|<1$ are obtained just as with $r_d>0$. /19

The basic difference of the mixer which uses a nonlinear superconducting film element with $r_d<0$ is displayed in its operation in the "fixed heterodyne current" regime. In this case, with $k_1<<1$ and $\sigma_c=\sigma_r>>1$

$$\eta \approx \frac{8\alpha \sigma_\Omega \sigma_r}{(1-\sigma_\Omega)^2 k_1} \tag{26}$$

and

$$\Omega_m \approx \frac{v_0}{l_T} \frac{1}{\gamma-1} k_2 . \tag{27}$$

The resulting expressions are evidence that the conversion efficiency of a mixer with such a nonlinear element can be made as large as desired as $r_\Omega \to |r_{do}|>>r$. It follows from these expressions however that such an increase in conversion efficiency will be accompanied by a corresponding constriction of the intermediate frequency band.

IV. Experimental Study of Microwave Conversion by Thin Superconducting Films

The results of the analysis presented above were tested experimentally in a laboratory model of a 3 cm range superconducting mixer.

As the nonlinear element of this mixer, 30-60 nm thick tin film, in the form of a 6-20 μm wide and 30-100 μm long strip was used. The resistance of a square of such films at T=300 K was 3-10 ohm, and the resistance ratio $\frac{R_{300}}{R_4}$=7-12.

For matching with the waveguide circuit, such a film was connected in the resonance segment by a two conductor flat halfwavelength film line. The low wave resistance of such a line provided a relatively wide frequency band of the strip resonator (Δf≳200 mHz) with low nonlinear element resistances (r<0.5 ohm). A change in posi- /20

tion of this resonator in the waveguide relative to its shorted end permitted regulation of the connection of the film element with the waveguide field within wide limits.

The mixer conversion efficiency was measured in different operating regimes in the experiment. As followed from the analysis presented, conversion efficiency η increased with decrease in resistance of the resistive region r (bias voltage U_0). Some deviations from this relationship corresponded to local features of the resistive section of the nonlinear element current-voltage curve. Greater conversion efficiency was observed in sections with higher dynamic resistance. In sections of individual specimens which corresponded to negative dynamic resistance on the current-voltage curve unperturbed by the microwave current, as the analysis predicts, mixing with amplification can be obtained, i.e., $\eta>1$.

In the absence of these regenerative effects, the conversion efficiencies of the samples studied were -(6-3) dB in optimum regimes.

The amplitude curve of the mixer studied is linear for signals of power $P<(10^{-9}-10^{-8})$ W. Saturation is noticeable in the regenerative regime with $P=10^{-8}$ W.

As has been noted, the ultimate rate of movement of the resistive region boundaries puts a top limit on the intermediate frequency range. It was therefore of interest to experimentally study the dependence of the conversion efficiency on frequency at comparatively high intermediate frequencies. These studies, conducted at frequencies of 30, 60, 90 and 120 MHz, showed that the mixer conversion efficiency barrier observed here is described well by the expression /21

$$\eta(\omega)=\eta_0\frac{\Omega^2}{\Omega^2+\omega^2},$$

which follows from the analysis carried out. For the tin specimens studied with a 2.5 ohm intermediate frequency load resistance, parameter $\Omega/2\pi$ was at least 100 MHz.

These experimental studies confirmed the correctness of the results of the analysis carried out and the practical possibility of the use of thin superconducting films for efficient mixing of microwave signals.

However, tin as a material for practical structures of such superconducting mixers leaves much to be desired. First and foremost, this is due to its low critical temperature ($T<4.2$ K) and therefore the need to operate with continuous evacuation of helium vapors from the cryostat. Besides, the low resistivity of tin essentially limits the possibility of wideband matching of such films with microwave and intermediate frequency circuits.

There is particular interest in films of high temperature superconductors in connection with this. Their use would permit both elimination of the need to evacuate helium vapors and to raise the operating temperature of such mixers to 12-15 K, where quite economical and relatively small closed cycle refrigerating machines have been developed. The first studies conducted in this area on niobium nitride films in the 3 cm range [10] showed that cryoelectric microwave mixers operating at 10-15 K based on such films can actually be developed.

V. Noise in Thin Superconducting Films

The maximum sensitivity of mixers and detectors is limited by the noise of the nonlinear element. There is therefore special interest in study of them. It is important to find out the level and spectrum of the natural noise of the element, their dependence on temperature and operating point, and to determine the optimum operating regimes of the element and the maximum sensitivity of the receiver. /22

As was noted above, a superconducting film in the resistive state is a complex object. The nonlinearity of the element is achieved at high current densities (10^5-10^7 A/cm^2). The appearance of

excess element noise can therefore be expected in this regime, a reliable calculation of which is extremely complicated.

We experimentally studied the noise of superconducting tin and niobium nitride films.

1. Tin Films

The noise of tin films was measured in a unit which permitted operation at temperatures of 1.7-4.2 K. The measurement range (120 Hz -20 kHz) was selected based on the possibility of obtaining reliable results, with allowance for the limitations on sensitivity of the measuring equipment and external adjustments. Since commercial equipment has a comparatively high noise level, a highly sensitive wideband, field effect transistor preamplifier was specially developed and fabricated for conduct of the studies. The input cascade of the amplifier was made of two carefully selected type KP 303 transistors connected in parallel. The total gain of the preamplifier was approximately 400. The natural noise level at the amplifier input was not over 1.7 $nV/Hz^{1/2}$ at frequencies $f>2$ kHz.

A cooled stepup transformer was connected in the measurement /23 circuit between the test element and the preamplifier input. It was located next to the test sample and operated at helium temperatures, which reduced the noise contribution of the winding. The transformer was made of a permalloy core with transformation ratio n=20. The noise level at the input of the circuit with the transformer was not over $8 \cdot 10^{-21}$ V^2/Hz.

To reduce the external adjustments, the test sample and the stepup transformer were shielded with a superconducting lead shield. The cryostat system was protected on the outside with a thick wall soft iron shield.

Two type U2-6 measuring amplifiers were used as the primaries. Each of them was tuned to 5 fixed frequencies and operated in the nar-

rowband regime ($\Delta f/f$=4-8%). The measured noise was recorded by means of a PDS-021 recorder. A I37 measuring amplifier connected to the X channel permitted investigation of the dependence of the noise level on the direct current regime of the element and, together with a filter, ensured isolation of the test element and recorder (protecting the element circuit from induction by the recorder input).

The adjustable direct current source for the voltaic cell powered circuit with the test element was connected through isolating filters, one made of high capacitance wire resistors and capacitors for low frequency noise cutoff and the other for protection from high frequency induction. The noise of the direct current source was monitored by measurement of the level with the sample in the normal state. The noise did not differ appreciably from the level with the sample deenergized.

The spectral density of the noise was measured at fixed frequencies with temperature T=1.8 K, in order to exclude temperature fluctuations caused by helium boiling. The measurement system was calibrated by means of calibration resistors, the noise temperature of which was assumed to be physically equal. /24

The measured noise of the test element as a function of direct current voltage on it showed the noise level does not depend on the resistance of the element (resistive region length) on the average. This is evidence that the transition RS regions between the resistive and superconducting regions of the film element play a decisive part in this case. At the same time, the local characteristics of the element, manifested by roughness of the current-voltage curve (abrupt change of dynamic resistance in a small section), significantly complicated recording by increasing the dynamic range of the noise measured. In connection with this, the test element was shunted in the measurement circuit by a small constant resistance (r=3 ohm), which smoothed out the effect of change of the dynamic resistance of the element. The observed noise can therefore be attributed to flucuations of the current flowing through the nonlinear element.

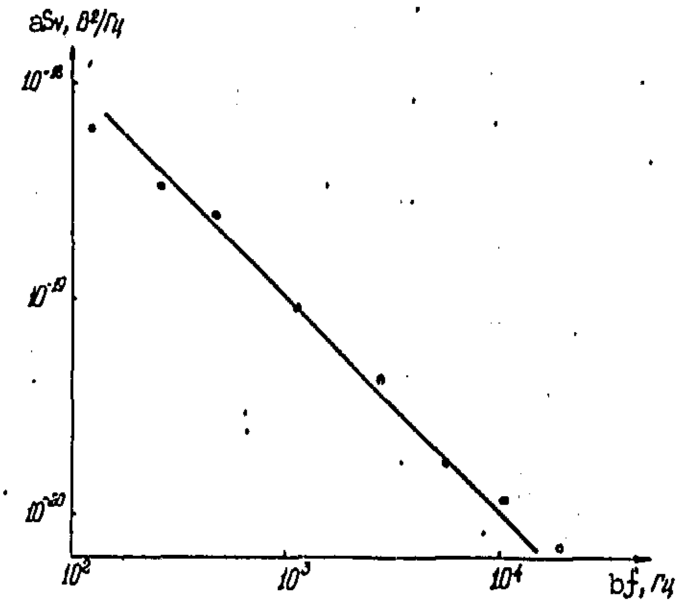

Fig. 6.

Key: a. Sv, V^2/Hz
b. f, Hz

A typical frequency dependence of the spectral density of the noise is presented in Fig. 6. The solid line corresponds to the I/f slope. It is evident that the observed noise decreases at the same rate. Its level permits a NER value of no worse than 10^{-13} W/Hz$^{1/2}$ to be obtained for a microwave detector with a voltage-power sensitivity of 10^3 V/W.

2. Niobium Nitride Films

It is necessary to operate at temperatures of 10-15 K to make measurements on NbN samples. The experimental unit permitted cooling of the test sample to the required operating temperature, regulation of the temperature in the assigned interval and its stabilization. /25

The basic component of the low temperature unit was a cryostat [11]. Helium vapors were used to cool the sample (waveguide section) to the assigned temperature. The required amounts of them enter the working space of the cryostat from a separate storage tank. This eliminated vibration, noise and other effects associated with helium boiling. The temperature was regulated by changing the amount of helium evaporated from the tank. High temperature stability was ensured by the corresponding equipment set through compensating heating of the mounting to which the test sample was connected. The same measurement amplifiers as in the case of tin films were used in the 20 Hz-200 kHz frequency range. To advance to the higher frequency region (f>30 kHz), for which the selective operating regime of the U2-6 amplifier did not provide, a set of filters was fabricated which were connected between the pre- and primary amplifiers. Since a de- /26

crease in level with increase in frequency is characteristic of the observed noise, a wideband stepup input transformer, placed in an Armco iron shield, was used in the 3 kHz-200 kHz range.

A preamplifier with a low noise type KT 368 A transistor at the input was specially fabricated for work at higher frequencies (2-30 MHz). The noise temperature of the instrument was approximately 125 K with R_{actual}=75 ohm. A S4-25 spectrum analyzer, calibration resistor set, preamplifier (f_0=250 MHz), Kh4-4 selective amplifier, a microwave circuit with klystron oscillators and power pack, a gas discharge tube noise generator, as well as an adjustable power pack with regime control circuits and circuits for recording the current-voltage curve and dynamic resistance of the test element are included in addition in the measurement complex. The noise of the power supply circuit was not over 30 K and was subtracted in treatment of the results.

The measurement equipment noise was comparable to and frequently even exceeded the test sample noise at high frequencies. In addition, the noise temperature of the preamplifier depends essentially on the resistance of the source. In order to eliminate possible errors associated with this, the measurement procedure consisted of the following. /27

After the required operating temperature was reached and stabilized, the current-voltage curve of the nonlinear element was recorded as a function of the dynamic resistance of the operating point. The noise level was recorded by means of the spectrum analyzer in several fixed regimes and compared with the noise of the calibration resistors, the resistance of which equals the dynamic resistance for the test element in each regime, at two temperatures (of the resistors), 77 and 293 K. This permitted accounting for and elimination of the measurement equipment noise in the best manner.

To increase measurement accuracy, the spectrum analyzer operated in the following regime: transmission band Δf=300 kHz; time constant of quadratic detector τ=3 ms. This ensured relative accuracy of read-

ing the noise level

$$\delta=\frac{1}{\sqrt{2\delta\tau}}=\frac{1}{\sqrt{2\cdot3\cdot10^{5}\cdot3\cdot10^{-3}}}<2{,}5\%,$$

and absolute reading accuracy

$$\Delta=\delta T_{meas}=0.025\ (200-600)\ K=(5-15)\ K$$

and finally, the absolute measurement accuracy of the element noise (with allowance for subtraction of the equipment noise)

$$2\Delta=(10-30)\ K,$$

where the larger values of Δ correspond to higher levels read, so that the relative measurement accuracy was $\delta'=10\%$.

In the acoustical frequency range, because of an increase of the detector time constant of the U2-6 amplifier to 5 s, the relative reading error over the range also was not over a few percent, only reaching $\approx$15% at the lowest frequencies. /28

The effective noise temperature curve of one sample (NbN, No. 185) is presented in Fig. 7 for the temperature interval in which its current-voltage curve is hysteresis free (Fig. 8).

The noise power decreases as $\approx f^{0.7}$ in the acoustical frequency range. It is noted that a level is reached which is independent of frequency near the lower limit of the measurement frequency range. The rate of decrease also decreases starting with frequency $f\approx 20$ kHz, and the spectral density of the noise at high frequencies reveals no dependence on frequency. Experimental estimation of the noise level at frequency f=250 MHz gives the same value as at f=30 MHz. This indicates that the noise spectrum in the 30<f<250 MHz interval is practically uniform.

At high frequencies and within the limits of experimental error, the noise power in the vertical section of the current-voltage curve

can be considered independent of the direct current regime of the test element.

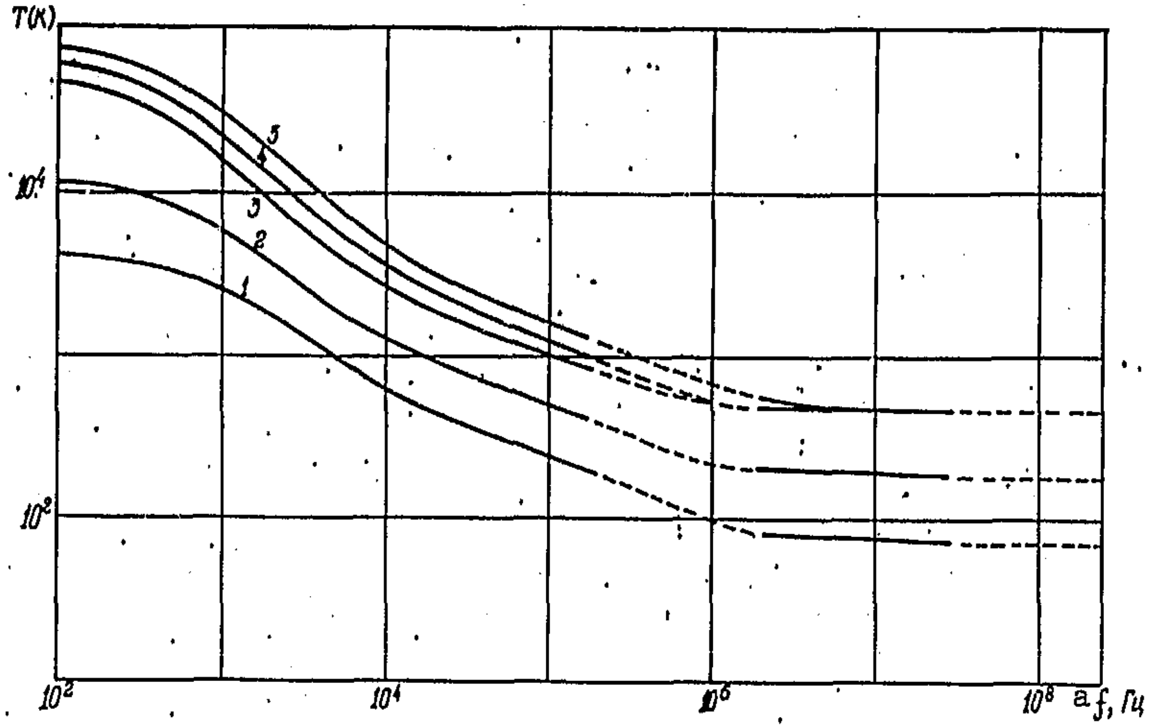

Fig. 7.

Key: a. f, Hz

The element noise depends on its operating temperature. A higher current through the film corresponds to a higher noise level ($T_{noise} \sim kI^{4/3}$).

In the acoustical frequency interval at temperatures close to T_r, below which the current-voltage curve of the element becomes hysteretic, a close to linear dependence of the effective noise temperature on resistive region length ℓ_r is observed. Noise intensity T_{noise} is practically independent of ℓ_r close to the critical temperature.

At least two components can be distinguished in the observed /30
noise: one determined by the temperature and independent of frequen-

cy and, within certain limits, of the operating point of the element; another component inversely proportional to frequency, which depends on the length of the resistive region at reduced temperatures, but this dependence is not found near the critical temperature. Both components apparently are determined by the transition RS regions between the resistive and superconducting regions of the element. The /31
frequency dependent component is most likely due to temperature fluctuations [12], and it is modified by the dependence of heat capacity on temperature.

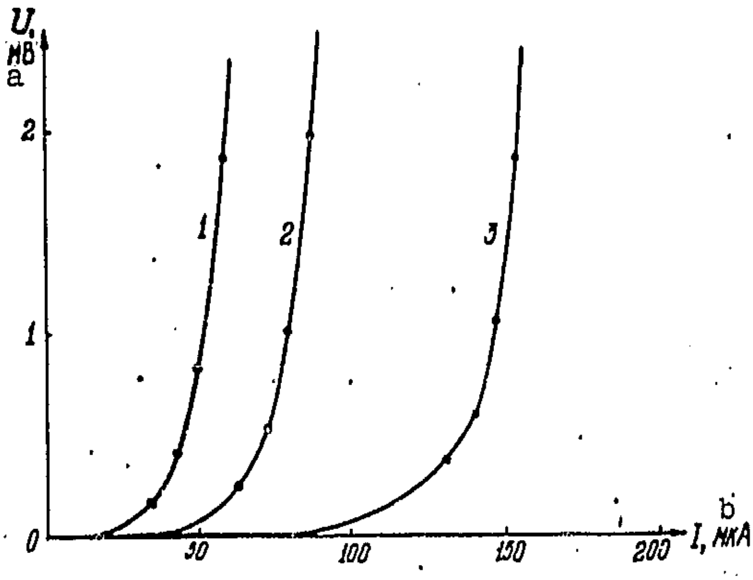

Fig. 8.

Key: a. U, mV
b. I, μA

For operation of the nonlinear element as a mixer, the noise level during action of the heterodyne on it is important. Such measurements were made at frequency f=30 MHz. The heterodyne was a deflector klystron ($\lambda \approx 3$ cm), the emission of which was optimum for mixer operation. Power was supplied to the test element by a waveguide circuit through a narrowband filter ($Q \approx 10^4$). The noise level of the element did not change when the heterodyne was switched on, on condition of equality of the dynamic resistances. The experimental data on the natural noise of the test element presented above thus give a correct idea of the noise level of the element in the mixing regime.

Direct determination of receiver noise temperature T_{rec} was carried out by means of the gas discharge tube microwave noise generator at $f \approx 9$ GHz. The high frequency preamplifier and spectrum analyzer indicated above were used as the intermediate frequency circuit.

The noise temperature of the receiver with a mixer at the input depends on the propagation ratio and noise of the nonlinear element of the mixer, as well as the noise of the intermediate frequency amplifier. To achieve high receiver sensitivity, the nonlinear element has to operate in the optimum regime with a low noise level. This requirement could not be completely fulfilled in our experiments for the following reason.

The test samples were a structure which consisted of the "working" portion of the film, a thin strip responsible for the nonlinear properties of the sample and the intermediate or low frequencies included /32 in the circuit, and elements which provide effective connection of the working part to the microwave field and isolation of the microwave and intermediate (low) frequency circuits. The wideband resonator provided effective easily adjustable connection with the electromagnetic field of the waveguide. The filter in the intermediate frequency circuit prevented leakage of the microwave power into the intermediate frequency circuit. The synthesis of these elements theoretically can ensure fulfillment of an important requirement, to lead all the microwave signal power into the working portion of the sample to achieve the maximum possible propagation ratio. This is confirmed by the corresponding measurements far from the critical temperature. As follows from the measured natural noise of the elements however, low working temperatures of the nonlinear element are undesirable for achieving high receiver sensitivity. It follows from Fig. 8 that T=12-10 K is preferable.

The niobium nitride samples we studied were made in the form of a planar circuit, all elements of which were sputtered to the same thickness from the same initial material with subsequent photolithography. In operation of the nonlinear element close to the critical temperature, the entire sample therefore also was close to T_c, and separate elements could even be in the normal state because of nonuniformity of the film. This considerably increased the undesirable losses and degraded the propagation ratio of the mixture upon approach to T_c. For this reason, the best result, the lower receiver

noise temperature of T_{rec}=7000 K, was obtained at T=11.89 K and η=0.087. It should be noted that, from the results of the studies conducted, the conclusion follows that this value can be substantially improved by operation of the nonlinear element in the optimum regime if the elements are connected and the filter of the sample is made of a superconductor with a higher T_c, of Nb_3Sn for example.

Conclusions

The results of the analysis of the possibilities of microwave signal conversion by superconducting films and the experimental studies are briefly reduced to the following. /33

1. Thin superconducting films changed to the resistive state by a current have high current-power sensitivity (over 10^3 A/W), and they therefore can be efficiently used as microwave videodetectors.

2. Efficient microwave frequency mixing is possible in these same films (conversion losses in the 3 cm range are 3-4 dB).

3. With separate signal and heterodyne connection elements present in the mixer, it is possible to mix and amplify microwaves (η>1), operating with the heterodyne in the highly overmatched regime.

4. In superconducting films with a normal end, the special configuration of which forms a section with negative differential resistance on the current-voltage curves, it appears possible to combine microwave mixing with regenerative amplification at intermediate frequencies (with corresponding constriction of the output frequency band).

5. The frequency characteristics of such superconducting mixers are limited in output (at intermediate frequencies) by the finite rate of change of the resistive region dimensions, and the correspond-

ing frequency band is approximately 1000 mHz, and the output frequencies are only limited at the bottom by a frequency of several gigahertz.

6. The temperature of the natural noise of a superconducting film element can be reduced to 50-75 K, which indicates the possibility of development of mixers with a low noise level (T_{mix}=200-300 K).

7. The required heterodyne power for a superconducting mixer is /34
approximately 30 dB lower than that of a semiconductor, which is a very valuable quality in the mm wavelength range.

8. The operating temperatures of such mixers made of high temperature superconductor films are 10-20 K, which permits the use of small size closed cycle refrigerating machines to cool them.

All this is evidence of the advisability of the use of superconducting films changed to the resistive state by current as efficient frequency converters in highly sensitive cryoelectronic microwave range receivers.

The authors thank A.P. Krut'ko and F.I. Korzhinskiy for presenting the niobium nitride samples, G.M. Blago for fabrication of the tin samples and A.V. Poladich for assistance in conduct of the experiments.

REFERENCES

1. Yeru, I.I., S.A. Peskovatskiy and A.V. Poladich, "Nonthermal discontinuity of current-voltage curve of thin superconducting film" FTT 15, 1599 (1973).

2. Yeru, I.I., S.A Peskavatskiy and A.V. Poladich, "Isothermal current-voltage curves of long superconducting films," UFZh 20, 903 (1975).

3. Skocpol, W.I., M.R. Beasley and Tinkham, "Self-heating hotspots in superconducting thin-film microbridges," J. Appl. Phys. 45, 4054 (1974).

4. Huebener, R.P., "Self-heating effects in thin-film type I superconductors," J. Appl. Phys. 46, 4982 (1975).

5. Yeru, I.I., V.A. Kashchey, S.A. Peskovatskiy and V.S. Sulima, "Current-voltage curves of long superconducting films in high and ultrahigh frequency fields," FTT 16, 3133 (1974).

6. Sulima, V.S., "Some characteristics of current-voltage curves of thin superconducting films in a UHF field," FTT 20, 2503 (1978).

7. Yeru, I.I. and S.A. Peskovatskiy, "UHF signal mixing and amplification by means of long, thin superconductors in the resistive state," Izv. uzov. Radiofizika 18, 1713 (1975).

8. Yeru, I.I., S.A. Psekovatskiy and A.V. Poladich, "Movement of resistive region boundaries in superconducting film with current," FTT 21, 2004 (1979).

9. Yeru, I.I., S.A. Peskovatskiy, V.S. Sulima and V.A. Kashchey, "Ultrahigh frequency signal mixing with conversion efficiency greater than unity in long superconducting film," Radiotekhnika i elektronika 20, 1112 (1975

10. Yeru, I.I., A.P. Krut'ko, S.A. Peskovatskiy and A.V. Poladich, "Mixing ultrahigh frequency signals in superconducting niobium nitride film," Radiotekhnika i elektronika 25/9, 2205 (1980).

11. Obolonskiy, V.A. and A.P. Krut'ko, "Cryostat for testing cryoelectric microwave instruments at temperatures of 4.5-30 K," Elektronnaya tekhnika, Ser. I, Elektronika SVCh 11, 85 (1979).

12. Clarke, I. and T.Y. Hsiang, "Low-frequency noise in tin and lead films at the superconducting transition," Phys. Rev. B 13, 4790 (1976).